STUDIES OF SLURRY FUELED PROPULSION SYSTEMS

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Purdue University

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STUDIES OF SLURRY FUELED PROPULSION SYSTEMS
FIFTH SEMIANNUAL PROGRESS REPORT

Office of Naval Research
Contract N00014-67-A-0226-0013

by

C. F. Warner

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JET PROPULSION CENTER
SCHOOL OF MECHANICAL ENGINEERING
PURDUE UNIVERSITY
LAFAYETTE, INDIANA

Errata

The aluminum slurry experimentally evaluated contained 75% aluminum and 25% decalin by weight. This correction should be made on page 24 line 15, Fig. III.A.6, page 28 line 12, DD form 1473 line 6 of the abstract.

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13 ABSTRACT

The development of an analytical model for the ignition and combustion of aluminum particles in a hydrocarbon carrier is presented together with the predicted length of cylindrical combustor required for the complete combustion of selected slurry fuels containing aluminum powders.

The results of the experimental investigation of the combustion efficiencies of selected fuels, JP-4, JP-5, decalin, 70% tetralin-30% decalin, and 70% aluminum-30% decalin, burned in a sudden dump combustor are presented and discussed.

Descriptions of two experimental combustor configurations and one flow visualization model combustor are given.

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Introduction:

The progress made during the period February 1, 1972, through July 31, 1972, will be discussed under the phase designations presented in the First Semiannual Progress Report dated September 14, 1970. Wherever appropriate, additional phase designations have been added to cover new subject matter not defined originally. This report, therefore, consists of a discussion of three phases: Phase I Development of the Analytical Model of the Sudden Dump Ramjet Propulsion System; Phase II Design of Combustors; and Phase III Experimental Evaluation of Combustors.

Phase I. Development of the Analytical Model of the Sudden Dump Ramjet Propulsion System.

I.A. Diffuser - no activity.

I.B. Stirred Reactor.

I.B.1 As was pointed out in Section B of Phase I of the Fourth Semiannual Progress Report, (1)* an alternative to the stirred reactor concept is the possibility of incorporating single particle combustion phenomena into a satisfactory combustion model for the combustion of clouds of particles as exist in a slurry fueled-air combustion system. Consequently, the results of a survey of literature pertinent to the combustion of aluminum particles was presented in Ref. 1. Pertinent

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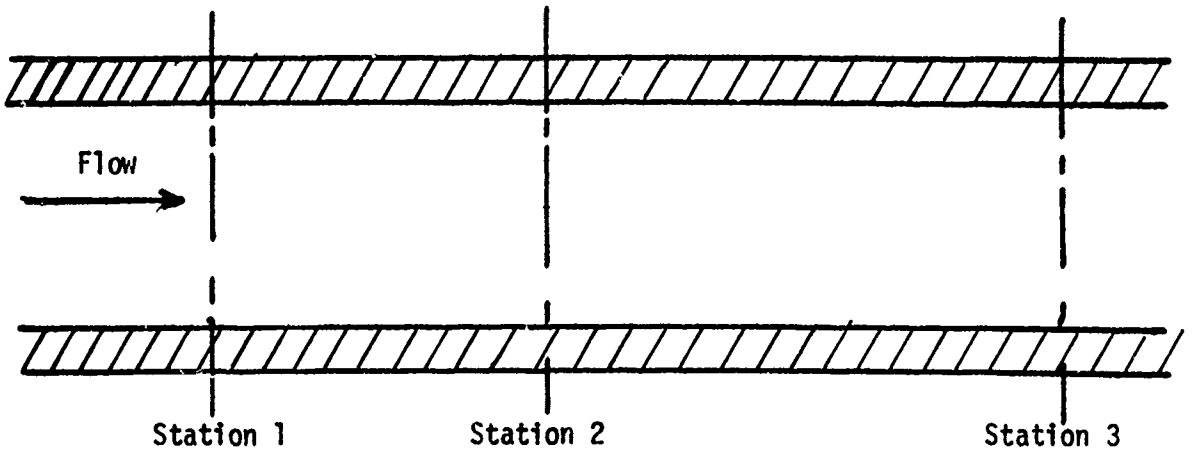
* Numbers in parentheses refer to the list of references at the end of each phase.



Distances 1-2 and 2-3 are unknown.

FIG. I.B.1. DIAGRAM OF FLOW SYSTEM FOR COMBUSTION MODEL

data obtained from the literature survey has subsequently been incorporated into the development of a preliminary analytical model for the ignition and combustion of aluminum particles such as might be incorporated into slurried fuel for use in an air breathing ramjet engine. Included are some computational results of the model together with an interpretation of these data in terms of the required length of the combustion volume of a slurry fueled ramjet.

I.B.2.1 The Model

The model is developed on the basis of the flow system illustrated in Fig. I.B.1. The following assumptions are incorporated:

(1) Flow is assumed to be steady and one-dimensional (flow properties are invariant with time or across any cross-section and the flow area is constant).

(2) The combustion chamber is assumed to be adiabatic and isobaric.

(3) The liquid (usually hydrocarbon) constituent of the fuel is assumed to react completely to an initial equilibrium before the metal ignition process begins; station 1 refers to the point at which initial equilibrium is complete, with the metal particles still at their inlet temperature.

(4) At station 2 the metal particles have been heated to their specified ignition temperature (or, if this is greater than the gas temperature, to thermal equilibrium with the gas). In case of the former, ignition occurs at this point.

(5) Particle combustion occurs in the section between stations 2 and 3. It is assumed that all particles behave identically throughout both the ignition and combustion processes, and that they have reacted to the specified completeness at station 3.

Additional assumptions will be made and discussed as the requirement for them becomes evident. The problem now becomes one of determining the values of various combustor parameters (such as length and temperature) required for ignition and "efficient" combustion of the metal

particles. The development which follows is based on a fuel consisting of decalin (decahydronaphthalene, $C_{10}H_{18}$) and powdered aluminum, but is applicable to a variety of fuels when their thermal chemical property values and combustion characteristics are employed in the computer programs.

I.B.2.2 The Ignition Section

The section between stations 1 and 2 can be considered the ignition section for the aluminum particles. For the purpose of making a first estimate of the residence time and section length required for ignition, it can be assumed that interparticular radiation heat exchange is unimportant to the ignition process; this is reasonable because the ignition temperature for aluminum particles, which is approximately equal to the melting-point temperature of aluminum oxide, seldom exceeds 2300 K. At this temperature the dominant mode of heat transfer to a particle is conduction. The relatively large air-fuel ratio needed for combustion of the fuel, particularly the decalin, results in a rather sparse cloud of aluminum particles, which renders radiative exchange improbable.

It is also assumed that the temperature of the gas mixture in the ignition section remains constant; that is, the mass fraction of aluminum in the mixture is sufficiently low as to render negligible the amount of heat lost by the gas during the particle heating process. It is found that if the fuel contains a high percentage of aluminum, with the resultant mass fraction increase being exaggerated by a decrease in the amount of air required for reaction, this assumption becomes questionable. For instance, if fuel which is 70 per cent (by weight) aluminum

is reacted with stoichiometric air to a temperature of 2300 K, it is found that as the particles heat up from an initial temperature of 300 K, the gas temperature drops to around 2200 K; this becomes the final thermal equilibration temperature for the particles and the gas. This development does not strongly affect the time required for equilibration, but it can affect whether ignition occurs (2250 K); for instance, if the particles are assumed to ignite upon reaching this temperature, neglecting the gas temperature drop results in the prediction that ignition will occur. Accounting for the drop in temperature indicates that no ignition occurs. Thus the chief effect of this phenomenon is to require somewhat higher hydrocarbon combustion temperatures for ignition of aluminum-rich fuels; the accuracy of the following residence-time analysis is not seriously affected.

Under these two assumptions -- negligible radiation and constant gas temperature -- a single-particle ignition model developed by Friedman and Macek (Ref. 2) becomes applicable. It has been established (Ref. 1) that the dominant feature of the particle ignition process is the melting of an oxide layer surrounding a particle, and that determination of the ignition delay time becomes a problem of heat transfer. Because very small particles (diameter less than 10 microns) and thus very low Reynolds numbers are involved, the problem is essentially that of convection from a stagnant gas; momentum transfer calculations, which indicate that small particles undergo rapid velocity equilibration with a moving gas, add credibility to this assumption. Under these conditions, for a spherical particle of diameter d at uniform temperature T in a stagnant ambient

medium of thermal conductivity k and temperature T_a, the heat flux is given by:

$$(1) \quad q = 2\pi kd\,(T_a - T)$$

If this is equated to the heat absorption of a sphere of heat capacity c, density ρ, and heat of fusion L at melting temperature T_m (933 K for Al), and the result is integrated from initial temperature T_o to ignition temperature T_i, the result can be rewritten in terms of the ignition time t_i:

$$(2) \quad t_i = (\rho d^2/12k)(c\,\ln((T_a - T_o)/(T_a - T_i)) + L/(T_a - T_m))$$

It will be noted that this predicts an ignition time dependence on the square of particle diameter; this is well correlated experimentally (Ref. 1).

With the ignition time thus determined, the required length of the ignition section can be established if the velocity of the gas in this section is known. This velocity can be found using the continuity of mass equation and the ideal gas law as follows: The gas density can be determined from the relation

$$(3) \quad \rho = P/RT = PM/R_uT$$

where ρ is the gas density, P is the system pressure (assumed constant), R and R_u are the specific and universal gas constants, M is the average gas molar weight, and T is the gas absolute temperature; note that the assumptions of no heat loss and negligible heat produced by reaction in the ignition section result in the observation that T is constant throughout. The gas velocity can then be determined from the expression:

$$(4)\quad \dot{m} = \rho A V, \text{ or } V = \dot{m}/\rho A$$

where $\dot{m}$ is the total mass flow rate, A is the flow cross-sectional area (assumed constant), and V is the velocity.

Thus it is seen that the ignition delay time and required ignition section length can be estimated if the following parameter values are known: Gas temperature; particle ignition, initial, and melting temperatures; particle heat of fusion, heat capacity, diameter, and density; system pressure, total reactant flow rate, flow cross-sectional area, and average gas molecular weight. Most of these values either have been established (the particle properties, for instance) or are specified by the configuration of the reactor and system; the notable exceptions are the gas thermal conductivity, temperature, and average molar weight. The thermal conductivity is estimated by considering the gas mixture to be air (about 80 per cent nitrogen and 20 per cent oxygen) and averaging the thermal conductivities for these two gases. Determination of the temperature and molar weight is performed using equilibrium calculations; it will be recalled that equilibrium at station 1 has been assumed and that negligible reaction occurs in the ignition section. Equilibrium calculations are performed by a computer program written by NASA researchers (Ref. 3).

I.B.2.3 The Combustion Section

Particle combustion takes place in the section between stations 2 and 3. Because of the reaction and heat release taking place, the mixture velocity, temperature, composition, and other properties vary

throughout the length of the section and a somewhat more sophisticated approach is required for analysis of the combustion process than is the case for ignition.

It has been determined (Ref. 1) that under proper conditions, aluminum is capable of burning in a vapor-phase diffusion flame, the fastest known particle combustion mechanism. A diffusion flame generally involves a burning-rate dependence upon the square of particle diameter, which can be expressed as the familiar "d^2 law":

$$(5) \quad d^2 = d_0^2 - \beta t$$

where d is the particle diameter at elapsed time t, d_0 is the initial particle diameter, and β is the so-called burning-rate constant.

An analysis of the problem of a spherical droplet burning in a quiescent atmosphere has been performed by Hellor and Glassman using the Shvab-Zeldovich formulation of heterogeneous combustion, details of which are described in Ref. 4. The results of this development indicate that the burning-rate constant should be given by the following expression:

$$(6) \quad \beta = (8k/\rho_{liq} c_p) \ln(1 + B)$$

where k is an average thermal conductivity for the gas surrounding the particle, ρ_{liq} is the density of the molten particle (since it is boiling, it is assumed to be above its melting temperature), c_p is an average gas specific heat, and B is the transfer number, a measure of enthalpy available to enthalpy required for fuel vaporization which is defined in the following expression:

$$(7)\quad B = (c_p(T_c - T_s) - y_{ox,c}\,\Delta H_R/i')/(h_{vap} + h_{liq})$$

where T_c is the temperature of the ambient medium, T_s is the particle surface temperature, $y_{ox,c}$ is the ambient mass fraction of oxidizer, ΔH_R is the heat of reaction per unit mass of fuel, i' is the stoichiometric coefficient (stoichiometric mass ratio of oxidizer to fuel), and $(h_{vap} + h_{liq})$ is the enthalpy per unit mass required to bring the fuel from its initial temperature to its boiling point and to vaporize it. Thus it can be seen that the burning-rate constant is expected to depend upon (among other things) the concentration of ambient oxidizer and the ambient temperature.

Values of most of the parameters appearing in Equations 6 and 7 are found tabulated or calculated with relative ease; notable exceptions are ρ_{liq} and T_s. The problem of evaluating the particle surface temperature, which is known to be a function of the system pressure, is handled by means of generating a third-order polynomial curve-fit based on surface temperatures calculated by Brzustowski and Glassman (Ref. 5) for three different pressures. From values for T_s of 2400, 2800, and 3200 K at pressures of 1, 10, and 50 atmospheres, respectively, the following expression for T_s in degrees K in terms of P in atmospheres evolves:

$$(8)\quad T_s = 2324.0 + 79.14\,P - 3.64\,P^2 + 0.04814\,P^3$$

Wilson and Williams (Ref. 6) used time-resolved photography to study the surface regression rate of laser-ignited Al particles in oxygen-argon atmospheres. The data from their experiment included tabulations of burning-rate constants as functions of system pressure and ambient

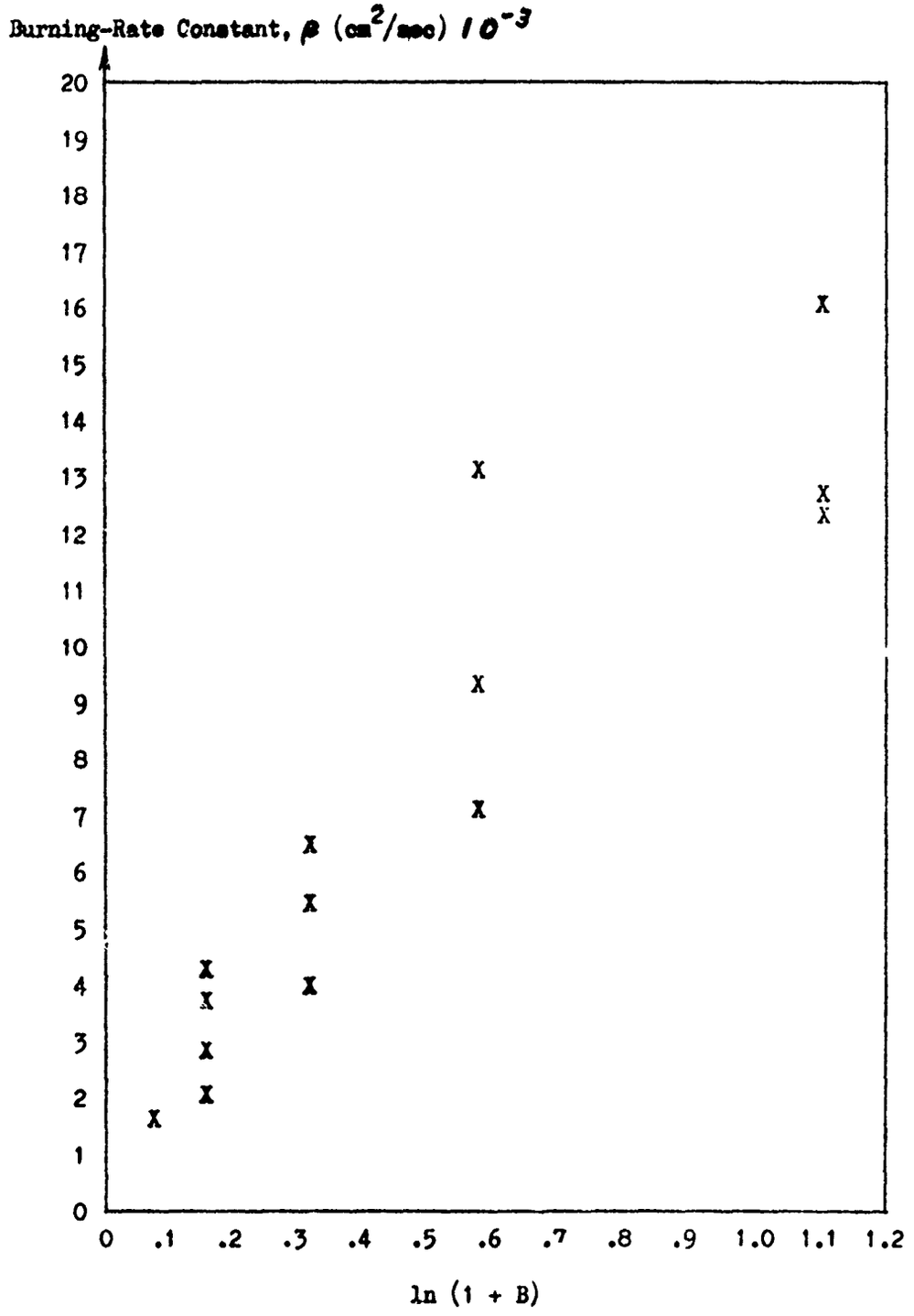


FIG. I.B.2. WILSON AND WILLIAMS EXPERIMENTAL BURNING-RATE CONSTANTS PLOTTED AS FUNCTIONS OF LN (1 + B)

oxidizer concentration. If the oxidizer mole fractions are converted to mass fractions and Equation 8 is used to estimate values of T_s, since T_c is known (300 K), the Wilson and Williams experimental conditions can be converted into transfer numbers by using Equation 7. The measured burning-rate constants can then be plotted as functions of the quantity $\ln(1 + B)$; this plot is presented in Fig. I.B.2. It must be noted that only those burning-rate constants which pertain to the "d^2 law" (some of the data was calculated on the basis of d^1 or $d^{1.5}$ laws) have been used. The form of Equation 6 suggests that the curve in Fig. I.B.2 should be a straight line; if such a line is drawn representatively through the data points, the slope of this line represents the term $(8k/\rho_{liq}c_p)$, and the problem of evaluating the liquid droplet density has been effectively bypassed. The expression chosen for use in this particular model is:

$$(9) \quad \beta = 0.015 \ln(1 + B)$$

It should be pointed out that the constant 0.015 was evaluated for a gas temperature of 300 K. That value may be in error for a gas temperature of 2500 K.

Equations 3 through 7 and 9 can be used to describe the varying gas velocities and particle burning rates along the length of the combustion section provided that a means can be devised of accounting for variations of the main parameters upon which these equations depend. This is done using a linearization technique to interpolate for values of these parameters between their predetermined "end values". The variables in question are gas temperature, average gas molar weight,

and ambient oxidizer mass fraction. Since equilibrium prevails at stations 2 and 3, the thermochemical equilibrium program previously mentioned can be used to establish the values of these three parameters at these two stations. Their values at any intermediate point during the combustion process are then interpolated linearly between these "initial" and "final" values, with the interpolation parameter being the reaction completeness at that point. For this purpose the reaction completeness is defined in terms of the fraction of the total amount of Al which has reacted; it is given by:

$$(10) \quad F_c = (d/d_0)^3$$

where F_c is the fraction of Al consumed and d and d_0 are the instantaneous and initial particle diameter, respectively. At any point, the value of one of the three parameters is given by an expression of the form (using ambient oxidizer mass fraction as an example):

$$(11) \quad y_{ox,c} = y_{ox,c,2} + F_c (y_{ox,c,3} - y_{ox,c,2})$$

where the subscripts 2 and 3 denote stations 2 and 3. The expressions for local values of temperature and average molar weight are similar.

A computational scheme can now be formulated which permits evaluation of gas temperature, mixture velocity, distance along the combustor axis, and reaction completeness for a "plug" of reacting mixture, all as functions of time elapsed from the instant this plug leaves station 2. The distance traveled by the plug at the point where a specified reaction completeness is reached can be interpreted as the required combustor length. The computational method evolves as a "rectangular

rule" numerical integration through time; it has the following general pattern:

(1) At time zero, conditions (gas velocity and temperature) are as calculated for the ignition section. The particle is at its initial diameter; distance traveled and fraction of Al consumed are zero.

(2) Equation 7 is used to calculate a value of B, the transfer number.

(3) Equation 9 is used to find a value for β, the burning-rate constant.

(4) A modification of Equation 5 is used to calculate a new value for particle diameter in terms of a time increment dt. The expression is:

$$d = (d_o^2 - \beta dt)^{1/2}$$

(5) Equation 10 is used to determine the fraction of Al consumed.

(6) Three equations of the form of Equation 11 are used to update the values of gas temperature, average gas molar weight, and ambient oxygen mass fraction.

(7) Equations 3 and 4 are used to update the values of gas density and velocity.

(8) The distance traveled during the current time increment is found by multiplying the time increment by the new velocity.

(9) Elapsed time is increased by another increment dt and steps 2 through 9 are repeated. This process continues until F_c (step 5) reaches a predetermined cutoff point. Distance traveled is continuously summed up so that total combustor length is available.

This numerical scheme has been incorporated, along with the ignition-section analysis discussed earlier, into a computer program termed BURNIT written in FORTRAN IV; the program should be usable on any computing system capable of handling that language. The program requires as input specified values for the following parameters: Initial particle

diameter, system pressure, initial fuel temperature, the time increment for integration, the air and fuel mass flow rates, the cross-sectional area of the combustor, and the values (determined from equilibrium calculations) of average gas molecular weight, mixture temperature, and ambient mole fraction of oxidizer for the fuels of interest (converted, within the program, to a mass fraction) at stations 2 and 3. Output from the program includes the calculated particle surface temperature; the elapsed time and distance traveled by a "plug" of mixture and the gas velocity and temperature, all within the ignition section; and the distance traveled, velocity, temperature, fraction of aluminum consumed, and the diameter of any particle for a mixture plug in the combustion section, all as functions of incremented time.

Program BURNIT has been used to perform a sample analysis on a cylindrical combustor of 4 in. inside diameter. Chamber pressure was specified as 10 atmospheres. The fuel was considered to be 10-micron aluminum particles suspended in decalin, with five different Al/decalin weight ratios studied: 30/70, 40/60, 50/50, 60/40, and 70/30. For each of these five fuels, three different fuel-air ratios were studied, corresponding to equivalence ratios (actual f/a ratio divided by stoichiometric f/a ratio) of 0.7, 0.8, and 0.9. Initial fuel temperature was considered to be 300 K, with inlet air temperature adjusted to provide an ignition-section mixture equilibrium temperature of 2300 K. Particle ignition temperature was specified to be 2250 K, thus insuring predicted ignition. An air mass flow rate of 1500 grams/sec was used, with fuel mass flow rates being varied to give the desired fuel-air ratios. The required reaction completeness (fraction of aluminum consumed) was 95

per cent. It was found that a time increment of .00001 or .00002 sec. was small enough to insure sufficient accuracy with the "rectangular rule" integration, but large enough to hold down the number of intermediate-point calculations to around 50.

Results from the 15 sample cases are presented in Table B.1. The equivalent flight Mach numbers presented are the flight Mach numbers which would be necessary to produce by inlet stagnation the indicated air temperature required for ignition (corresponding to an ignition section equilibrium temperature of 2300 K). These Mach numbers are based on a flight altitude of 20,000 ft. and a standard atmosphere (T = 250 K); they are included as an indicator of whether auxiliary heat addition should be necessary for ignition of a given fuel at a specified flight speed.

I.B.2.4. Results and Conclusions

Because of the approximations involved in the formulation of the model, particularly in the assumption of perfect mixing, it must be conceded that the model represents a virtually optimum system for efficient combustion and that performance figures which it predicts would probably not be realizable in an actual combustor. It has been proposed by Brzustowski (Ref. 5) that aluminum will not burn in a diffusion flame in an atmosphere containing too low an oxidizer mole fraction; a lower limit of around 0.1 was suggested. Since most of the equilibrium calculations performed during analysis of the 15 sample cases revealed oxygen (O_2 is considered the only oxidizer) mole fractions at station 2 of 0.08 or less, it is possible that a real system operating under the studied conditions would involve some aluminum combustion mechanism other than a diffusion flame. The most likely alternative is a surface

TABLE B.1

Analytical Results for Sample Cases

Aluminum-Decalin Weight Ratio	Equivalence Ratio	Required Air Inlet Temp. (K)	Equivalent Flight Mach No.	Maximum Temp. (K)	Required Combustor Length (cm)
30/70	0.7	1175	4.30	2613	16.98
30/70	0.8	980	3.80	2640	21.31
30/70	0.9	755	3.17	2627	32.60
40/60	0.7	1280	4.55	2726	16.38
40/60	0.8	1100	4.10	2758	19.69
40/60	0.9	910	3.62	2776	23.33
50/50	0.7	1385	4.78	2858	16.02
50/50	0.8	1225	4.41	2885	18.56
50/50	0.9	1063	4.04	2913	22.27
60/40	0.7	1518	5.00	3029	15.90
60/40	0.8	1410	4.80	3078	17.81
60/40	0.9	1230	4.42	3102	20.48
70/30	0.7	1750	5.50	3209	15.25
70/30	0.8	1636	5.25	3258	16.57
70/30	0.9	1524	5.05	3309	18.12

Required air inlet temperature refers to an ignition section equilibrium temperature of 2300 K. Equivalent flight Mach number is the Mach number required to reach this temperature by stagnation for standard air at 20,000 ft. (250 K). Maximum temperature is based on 95 per cent reaction of aluminum.

reaction, in which case the particles would burn according to a "d^1 law", and the burning times would increase considerably. It is also possible that there is some lower limit of ambient oxygen mole fraction (other than zero) below which aluminum will not burn at all; obviously, were this limit reached as available oxidizer was depleted during metal combustion, combustor performance might be seriously affected.

Although the model may thus be quantitatively inaccurate, it can probably be used for the prediction of general trends in the effects of various system parameters upon performance. Based on the results presented in Table 5.1, the following observations can be made:

(1) Increasing the percentage of aluminum in the fuel increases the performance as indicated by the peak temperature.

(2) Increasing the percentage of aluminum in the fuel decreases the required total combustor length.

(3) Increasing the equivalence ratio (when operating in the fuel-lean region) increases performance.

(4) Increasing the equivalence ratio decreases the inlet air temperature required for aluminum ignition.

In general, it appears that there are trade-offs involved in the design of slurried-fuel ramjet combustion systems. Most noteworthy among these is the relation between performance and ease of ignition; increasing the aluminum loading in the fuel to increase performance complicates the ignition problem. This can be partially offset by operating at higher equivalence ratios (closer to stoichiometric in the fuel-lean region), but an increase in required combustor length results. One possible solution to the ignition problem would involve the use of staged combustion. Mixing the fuel initially with stoichiometric

amount of air for reaction of the hydrocarbon constituent would maximize the initial reaction temperature, permitting minimum required air inlet temperature or auxiliary heat addition for ignition of the metal. Secondary air could then be added for reaction of the metal.

It should also be pointed out that the preliminary combustion model neglects any heat transfer from the flame zone or recirculated combustion products. Such heat transfer effects could alter the previous conclusions.

I.B.2.5 Reference List

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I.C. Composition of Combustion Products

I.C.1 The NASA Computer Program (NASA SP-273) for calculating the composition of combustion products was modified to accommodate slurry fuels containing aluminum powder in a hydrocarbon carrier.

I.D. Gasdynamic Model of Sudden Dump Combustor
Contributed by Dr. S. N. B. Murthy

I.D.1. Introduction

It is proposed that the sudden dump combustor performance -- fluid mechanics and combustion -- may be studied using a model to be referred to here as an "aerodynamic flame-holder model" or "aerodynamic flame-stabilizer model".

Essentially, it consists in dividing the fuel-air mixture into two jets within the combustor so that one of the jets, moving initially opposite to the direction of the flow, may after turning around and after some recirculation, interact with the other (forward facing jet) and produce a stable flame.

Some preliminary thoughts on the development of such a model are presented here.

I.D.2. Flow Pattern in the Combustor

Consider four intersecting jets, as shown in Fig. I.D.1., emanating symmetrically from around the circumference of the combustor in a given radial plane. Let the four jets have equal diameter d. On intersection, they may be expected to yield two jets located at the axis, one forward facing (say, diameter d_f) and another backward facing (say, diameter d_b). Assuming incompressible flow, it follows that

$$\cos \beta = \frac{d_f - d_b}{4d}$$

where β is the angle of inclination of each of the four intersecting jets to the axis in a meridional plane. It follows then that d_f and d_b can be adjusted by a choice of β for given d.

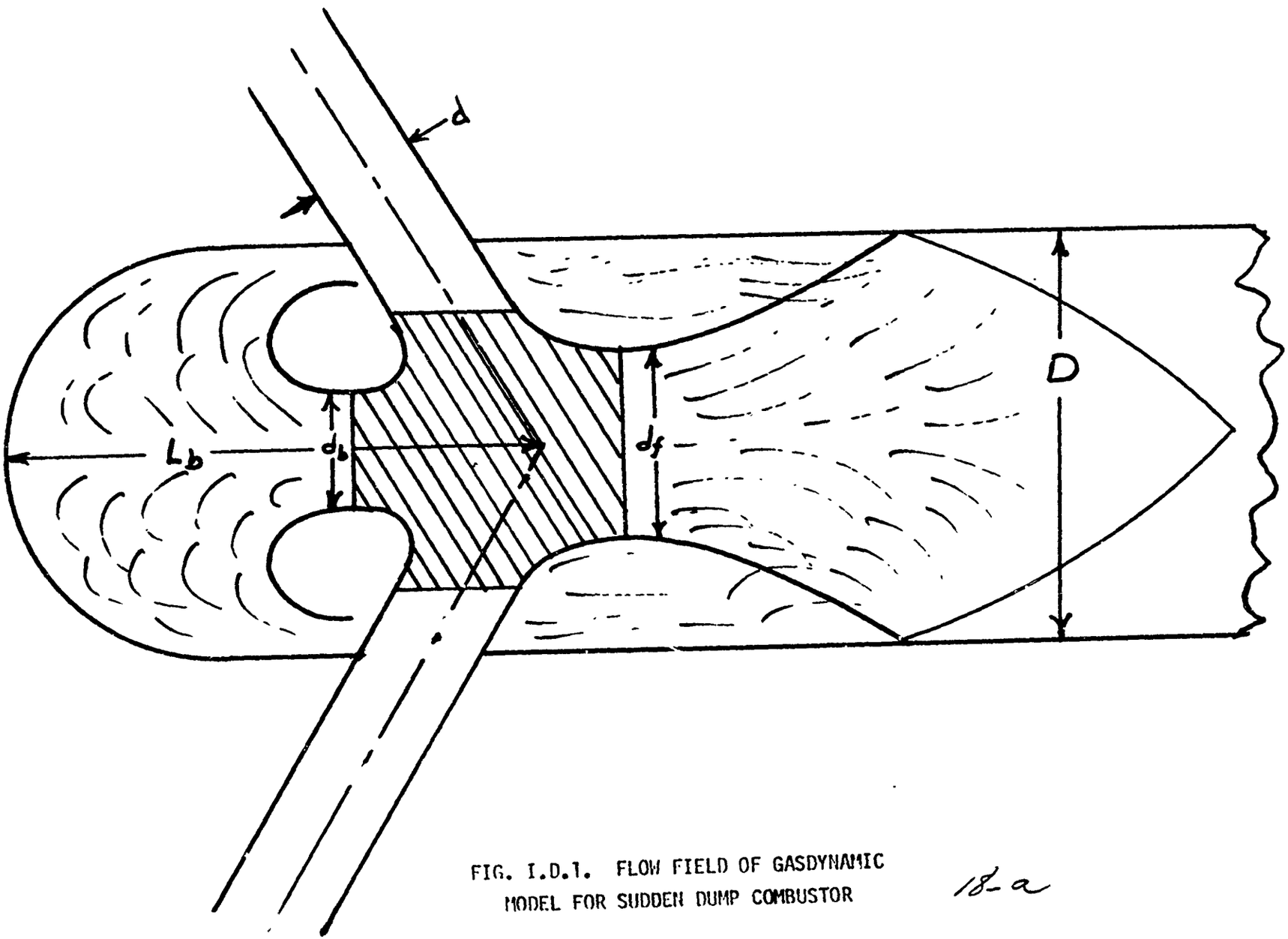

FIG. I.D.1. FLOW FIELD OF GASDYNAMIC MODEL FOR SUDDEN DUMP COMBUSTOR

Consider now the backward facing jet of dia d_b. If the back wall of the chamber, located at say $x = -L_b$, has a shape $y_b = f(x)$, it is possible to determine the spread of the jet d_b on its impacting the wall.

In a final step, it is possible to determine the following:

(a) the multiple recirculation cells and the wall flow resulting from the impacting and turning of the backward facing jet;

(b) the spread of the forward facing jet of dia d_f and

(c) the mixing characteristics of the wall flow from the rear and the forward facing jet.

Assuming non-reacting flows under isothermal conditions, the foregoing three calculations can be conducted under various approximations pertaining to viscosity effects at boundaries (jet and wall) and the existence or otherwise of turbulence in the jets and in the recirculation zone.

Several characteristic lengths and times in relation to the jet spreading, mixing and recirculation zones can be examined with reference to D, the diameter of the combustor, d, β, L_f, the velocity of the intersecting jets and some physical properties of the medium.

I.D.2.1. The first refinement in this cold flow analysis should deal with the formation of the stagnation zone at the axis in the region of intersection of the four incoming jets. The shape, location and possibly structure of the stagnation zone should be determined for chosen d and V_i, the velocity of the incoming jets.

We then have the four intersecting jets and the stagnation zone as a practically fixed fluid mass, assuming a strong enough momentum flux in the incoming jets. The flow coming from the rear wall and

later along the chamber wall will interact with the four jets of incoming fluid while going round them. In cold flow conditions, some mass and momentum exchanges may occur in a mixing zone around the incoming jets.

I.D.2.2 In performing any analysis of sufficient refinement, it is necessary to depend here on experimental results. The necessary experimental studies may be divided into three parts:

(a) optical observations of flows;

(b) wall measurements and

(c) probe measurements, with probes embedded in the flow. For example, the four incoming jets may be replaced by four probes connected to a stagnation chamber at the centre with two jets going out axially, one forward and one backward. Then, one can make measurements with probes suitably placed on the walls of the tubes and the stagnation chamber.

The data obtained from such experiments with d, V_i, L_b and $y_b(x)$ as variables will assist us in obtaining further details to be incorporated in the theoretical models. The correlation of the data must be based upon an appropriate combination of jet dimensions, mean velocity fluctuations, average dimension of turbulent eddies and the local viscosity, as well as residence times in the different zones.

I.D.3. Combustion Model (Pre-mixed Gases)

The model is based upon three sub-models as follows:

(a) the spread of flames in ducts when a pressure gradient is present along the flow because of flow cross-sectional area changes.

(b) the mass exchange between the recirculation zone and wall flow.

(c) the heat transfer and ignition processes in the recirculation zone.

(d) the entrainment of wall flow in the forward facing jet d_f.

Thus, for a given mixture ratio of a chosen combustible mixture, it is in principle possible to obtain similarity rules governing the behavior of a stable flame. The ambiguities in the calculation will pertain to (i) the profile of the state properties across the duct in different axial positions, (ii) the hypothesis for determining jet spread, mixing and flame layer dynamics and (iii) the influence of internal instabilities in the different zones on the overall flow configuration.

I.D.3.1. It is clear that the theoretical model can again be improved with data from experimental combustors. There will of course be questions regarding the suitability of imbeddable probes both from the point of view of the probes and from the point of view of the disturbance they may introduce into the flow.

I.D.4. Combustion Model (Actual Propellants)

The multi-phase character of the incoming propellant stream and the influence of internal instabilities associated with such a multi-phase character are the two new features here compared to Section I.D.3.

Phase II. Design of Combustors

II.A. Development of Fuel Injectors - no activity.

II.B. Design and Development of Combustors

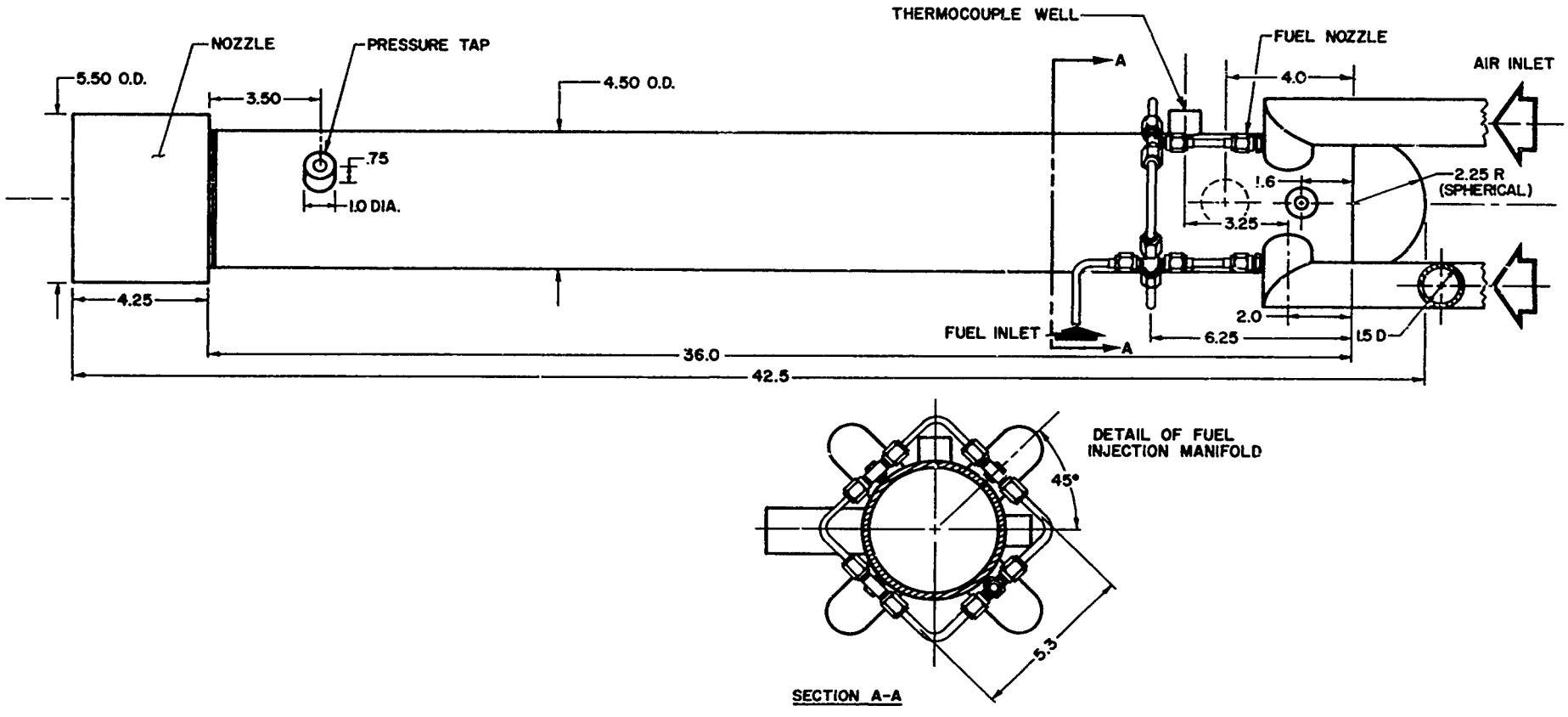

FIG. II.B.1. SUDDEN DUMP COMBUSTOR

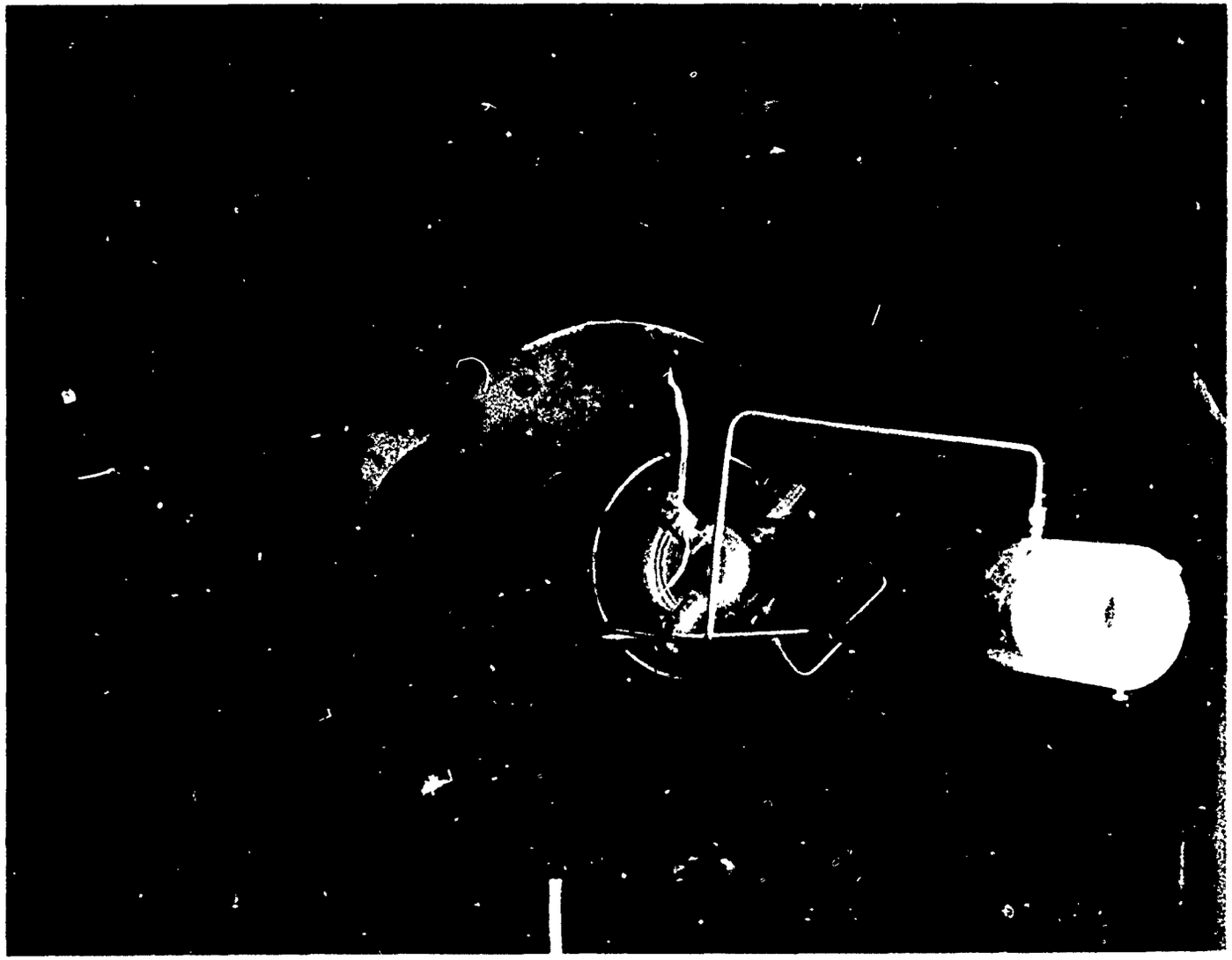

FIG. II.C.1. FLOW VISUALIZATION MODEL OF SUDDEN DUMP COMBUSTOR

II.B.1 A combustor similar to that shown in Fig. II.B.1. but with an air inlet angle of 45° with the combustor axis was designed and fabricated.

That combustor has been installed in the test facility. Experimental results obtained with the 45° air inlet combustor will be compared with those obtained with the 90° combustor.

II.C. Plexiglass Flow Visualization Model

II.C.1. In the development of the analytical model of the sudden dump combustor an understanding of the gas dynamic flow patterns is of importance. As an aid in obtaining such an understanding, a flow visualization model was designed and fabricated. Cold air is supplied to the flow model from the air supply employed in combustion experiments. The initial plexiglass model, shown in Fig. II.C.1. has the same dimensions as those of the 90° combustor shown in Fig. II.B.1. Additional plexiglass models will be fabricated as the development of the analytic model progresses and the need for experimental verification and evaluation of pertinent parameters becomes evident.

Phase III. Experimental Evaluation of Combustors

III.A. Experimental Evaluation of Combustors Employing Thrust Stand Measurements

III.A.1.1. Introduction

A series of experimental combustion firings were conducted employing the sudden dump combustor having 90° air inlet angles (shown in Fig. II.B.1.) installed on the thrust stand (shown in Fig. III.A.1.)

FIG. III.A.1. EXPERIMENTAL COMBUSTOR MOUNTED ON THRUST STAND

of the Combustion Research Laboratory. The details of those experiments and the results obtained will be discussed in subsequent sections of this report.

III.A.1.2. Experimental Facility

The experimental combustor, air heater and transition section were mounted on a thrust stand as shown in Fig. III.A.1. Inlet air was supplied to the air heater through flexible lines arranged so as to contribute no axial force to the thrust stand. Aviation fuel JP-4 was employed in the air heater. The static temperature and the static pressure of the preheated air could be controlled to desired values which were representative of altitude and Mach number conditions.

A series of convergent graphite nozzles were employed for all of the experimental firings reported herein.

Ignition was obtained by the flame of an electrically ignited methane-oxygen torch injected two inches downstream of the air inlets of the combustor.

The hydrocarbon fuels were injected through Spraying Systems Co. Vee Jet Nozzles numbers 1/8 WV11002 and 1/8 WV9506.

The aluminum-decalin slurry fuel was injected through circular orifices approximately 0.16 in. in diameter.

A sharp edged orifice (with flange taps) was placed in the air supply line. A turbine type flow meter was employed to evaluate the hydrocarbon fuel flow rates. The static temperature at the exit plane of the air heater was measured using a chromel/alumel thermocouple probe. The static pressure at the same location was measured by

a pressure transducer. The static pressure just upstream of the converging exhaust nozzle was likewise measured by a pressure transducer.

The slurry fuel was supplied via the water pressurized piston tank arrangement depicted as the vertical cylinder adjacent to the combustor shown in Fig. III.A.1. The slurry fuel flow rate was calculated from both measurements of piston tank volume and time; and a turbine type flow meter placed in the water feed line of the piston tank.

A force cell was employed to evaluate the static thrust of the combustor.

III.A.1.3. Experimental Procedure

All experiments were conducted by first establishing the desired air inlet temperature (approximately 1260 R) and the approximate static pressure desired upstream of the exhaust nozzle. The ignitor was then activated and fuel flow initiated. As soon as steady state combustion was established the ignitor was turned off. In the case of the slurry fuel experiments, the ignitor was activated during the complete experiment.

The initiation of combustion resulted in a rise in the static pressure of the combustor. For example, for a precombustion pressure of approximately 60 psia, the static pressure in the combustor with combustion would be 105 psia.

The air inlet temperature and air flow rate were approximately unaffected by the initiation of combustion since a backpressure plate with restricted flow passages is installed between the air preheater and combustor air inlet tubes.

The initial fuel flow rate was established to provide an equivalence ratio of approximately one. The fuel flow rate was then changed to cover a range of equivalence ratios both above and below one. When the fuel flow rate resulted in either unstable combustion or no continuous combustion after ignition for a given air flow rate, the series of experiments was terminated. Thus the experimental results reported in Section III.A.1.6. are limited to those experiments during which stable combustion was established.

The duration of the steady state combustion portion of the experiments was approximately two seconds.

The fuels employed were:

1. JP-4
2. JP-5
3. Decalin
4. 70% Tetralin and 30% Decalin
5. 70% Aluminum and 30% Decalin

Fuels no. 4 and no. 5 were provided by the Naval Weapons Center, China Lake. The required thermodynamic properties for those fuels were provided by Mr. G. W. Burdette, Fuel Department, Propulsion Division of the Naval Weapons Center.

III.A.1.4. Data Reduction

The combustion efficiencies based upon thrust obtained with the various fuels employed with the 90° air inlet sudden dump combustor were calculated using equation A.1.4.1 based upon air specific impulse parameters.

$$\eta = \frac{S_a - S_{a_a}}{S_{a_i} - S_{a_a}} \qquad A.1.4.1$$

where S_a = Air specific impulse = $\dfrac{F_s + p_o A_s^*}{\dot{m}_a}$

F_s = measured thrust, lb.

p_o = ambient static pressure, psia

A_s^* = nozzle throat area, sq. in.

$\dot{m}_a$ = measured mass flow rate of air, lb/sec

S_{a_i} = ideal air specific impulse = $\dfrac{\frac{\dot{m}_t V_e^*}{g_c} + A_s^* (p_e - p_o) + p_o A_s^*}{\dot{m}_a}$

$\dot{m}_t$ = total mass flow rate = $\dot{m}_f + \dot{m}_a$

$\dot{m}_f$ = mass flow rate of fuel, lb/sec

$\dot{m}_a$ = mass flow rate of air, lb/sec

V_e^* = theoretical exit velocity of combustion products based on NASA computer program

p_e = static pressure at nozzle exit plane

S_{a_a} = air specific impulse (no fuel) at air static inlet temperature = $\dfrac{\dot{m}_a V_{e_a}^* / g_c + p_{e_a} A_s^*}{\dot{m}_a}$

$V_{e_a}^*$ = theoretical velocity of air at exit plane of nozzle based on static temperature at air heater outlet

p_{e_a} = static pressure of air at nozzle exit

The Mach number in the combustor based upon the specific heat ratio, molecular weight and static temperature of the combustion products as obtained with the NASA Computer program was computed as a pertinent parameter.

In general, the Mach number in the combustor was approximately 0.14 or 0.25 obtained with exhaust nozzles having throat diameters of 1.79 in. and 2.50 in. respectively.

III.A.1.5. Presentation of Experimental Results

The combustion efficiency as determined employing equation A.1.4.1. is plotted as a function of the equivalence ratio

$$\frac{(\dot{m}_f/\dot{m}_a)\ \text{measured}}{(\dot{m}_f/\dot{m}_a)\ \text{stoichiometric}}$$

for the various fuels in Figs. III.A.2-6. Each Figure will be discussed separately in the following section.

III.A.1.6. Discussion of Results

III.A.1.6.1. JP-4

In order to obtain a basis for comparing the results obtained with decalin and decalin mixtures, it was decided to determine the combustion efficiencies of the 90° air inlet combustor employing the conventional hydrocarbon fuels, JP-4 and JP-5. The results obtained with JP-4 are presented in Fig. III.A.2. All of the experiments with JP-4 were conducted at a combustor Mach number of approximately 0.13. With the exception of the low pressure experiments (81-84 psia), combustion efficiencies of approximately 90% were obtained.

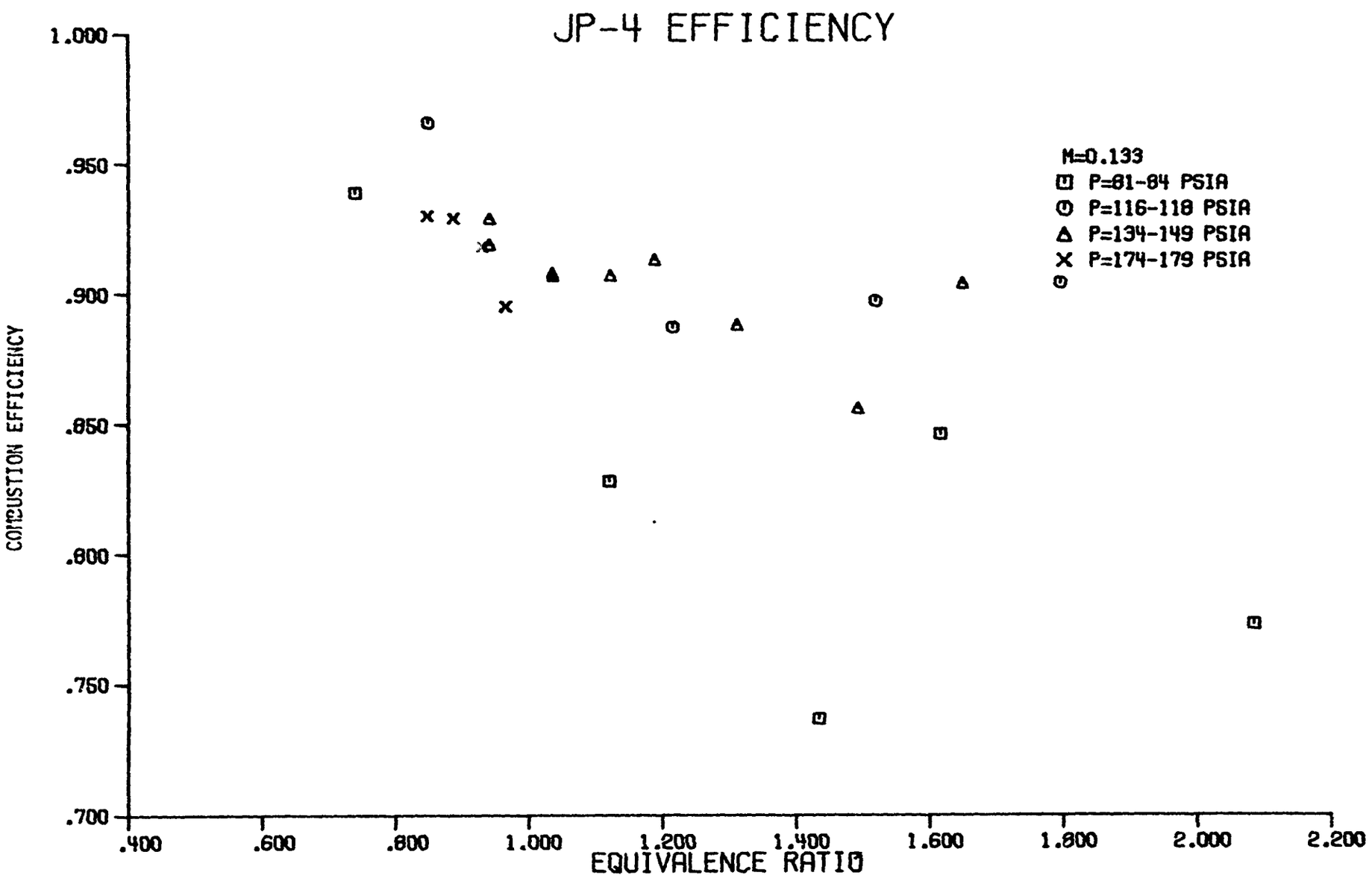

FIG. III.A.2. COMBUSTION EFFICIENCY FOR JP-4 27-a

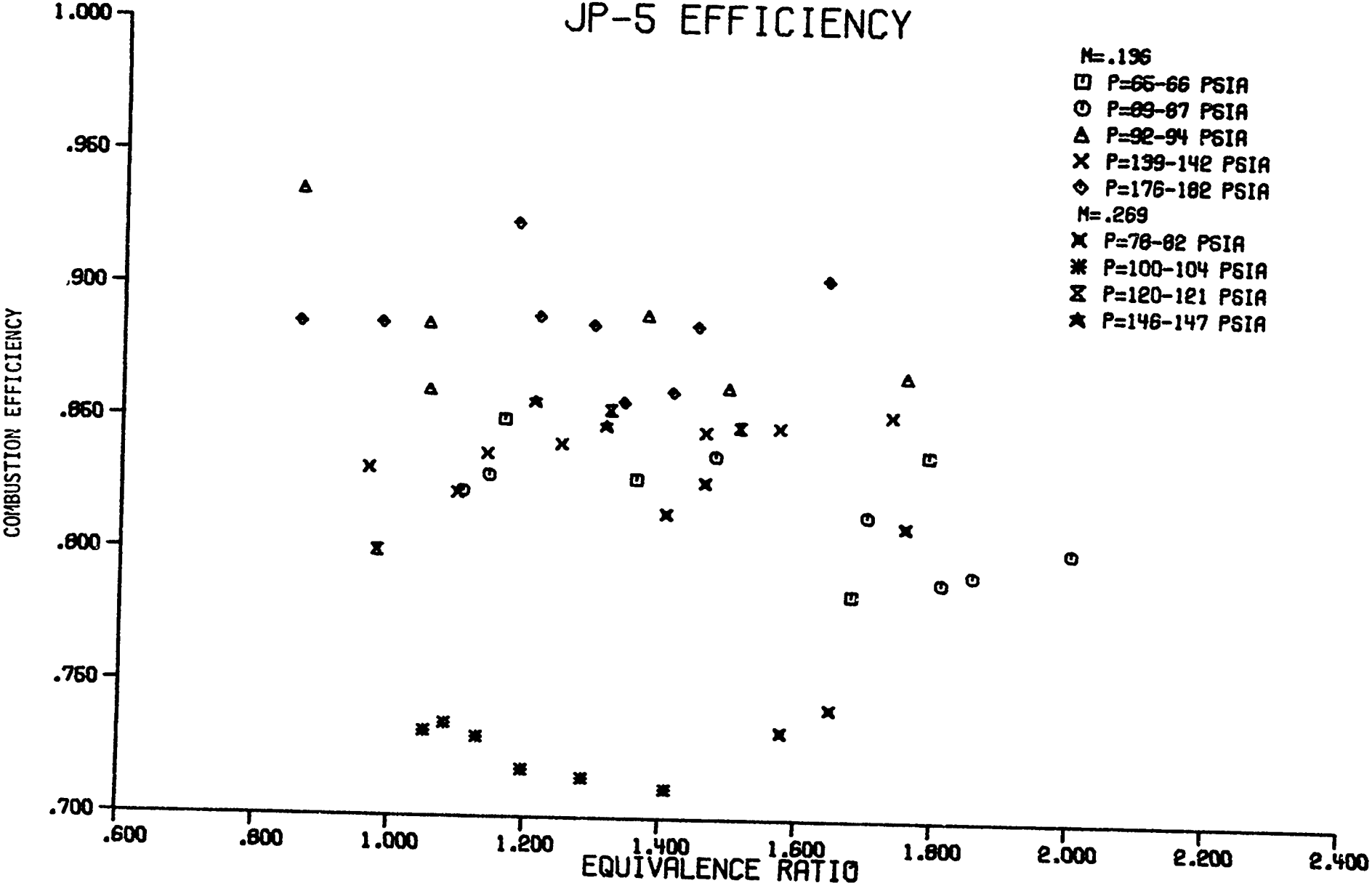

FIG. III.A.3. COMBUSTION EFFICIENCY FOR JP-5 27-E

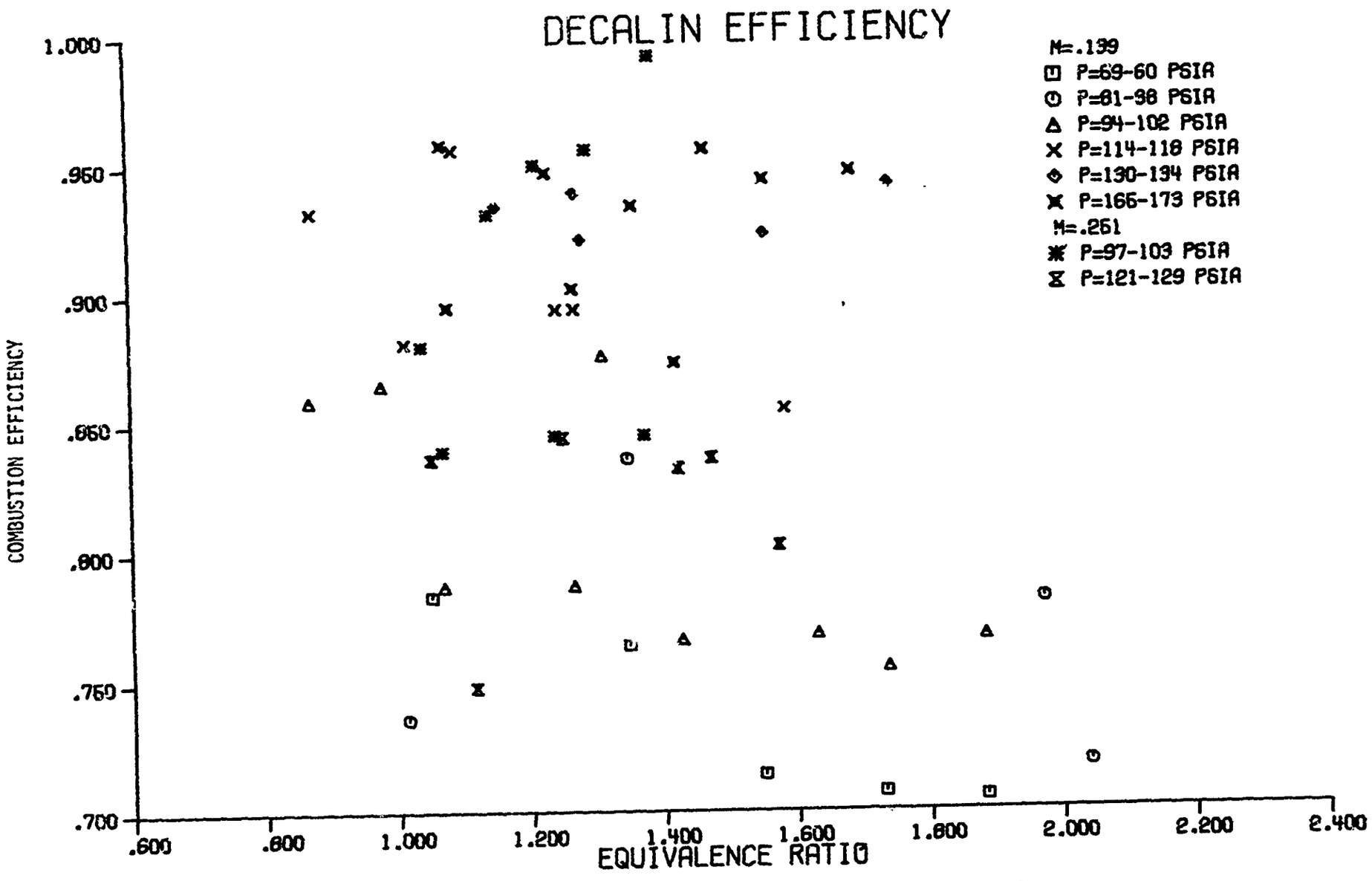

FIG. III.A.4. COMBUSTION EFFICIENCY FOR DECALIN 37c

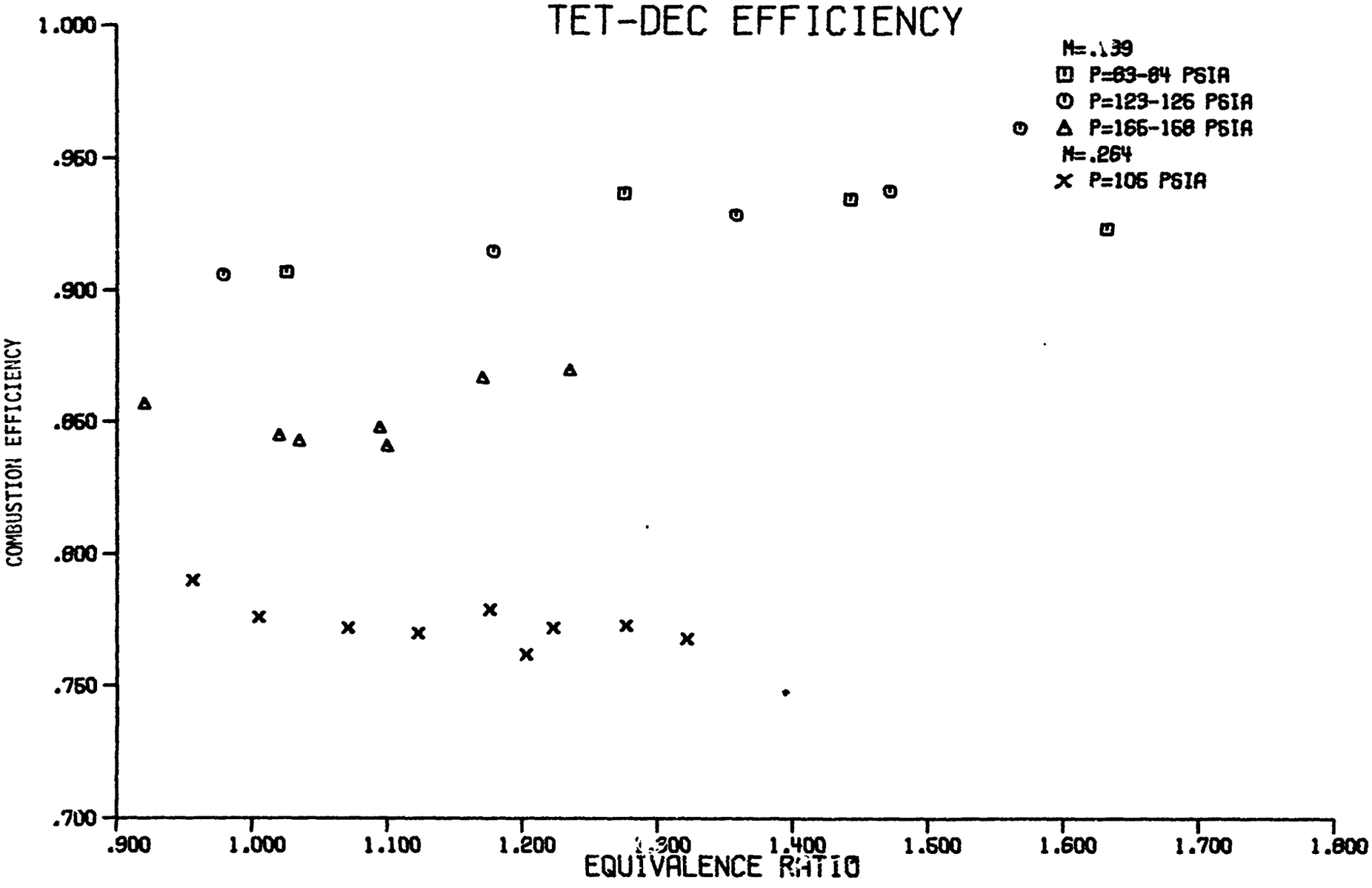

FIG. III.A.5. COMBUSTION EFFICIENCY FOR 70% TETRALIN-30% DECALIN MIXTURE 27-d

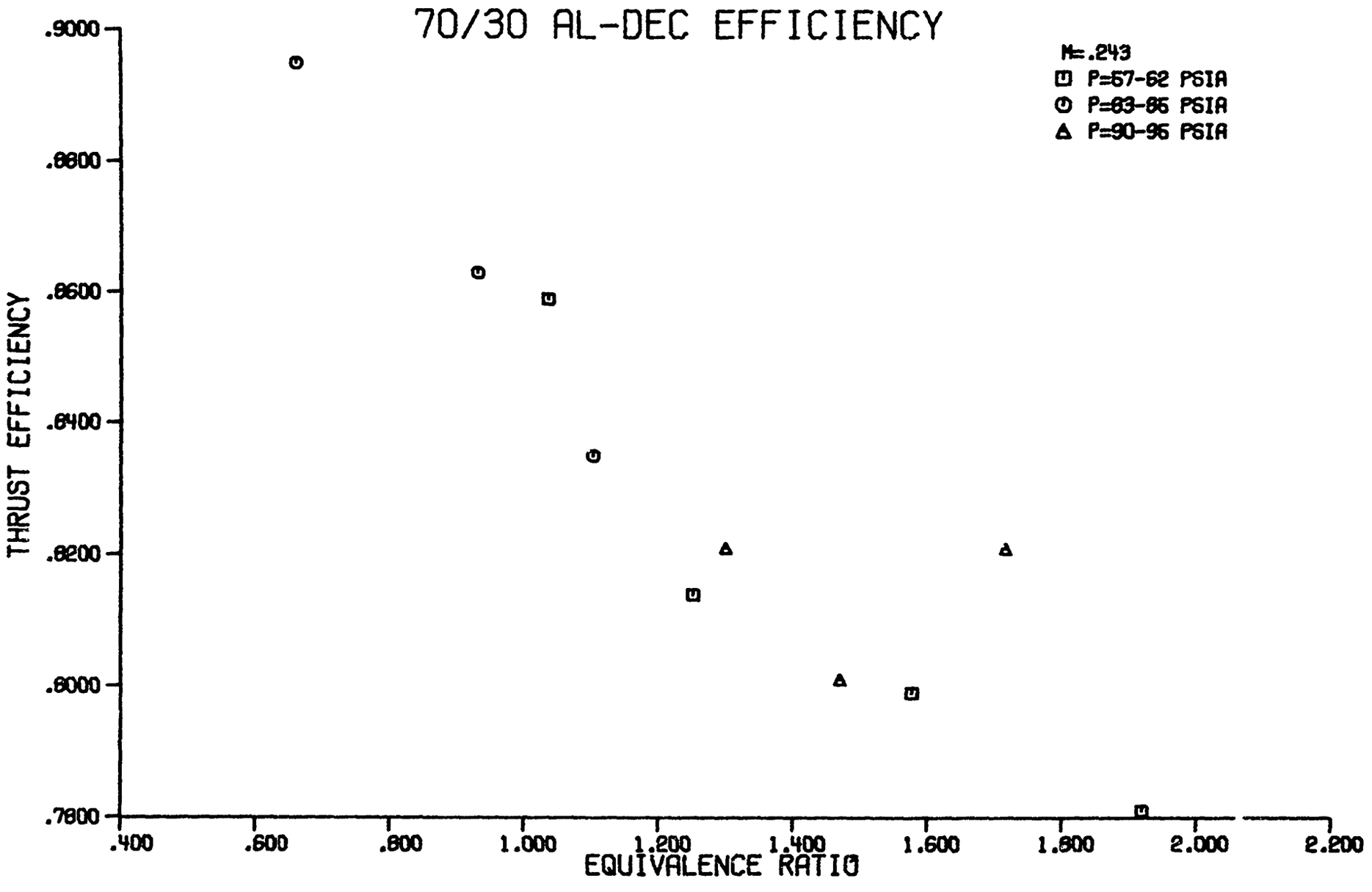

FIG. III.A.6. COMBUSTION EFFICIENCY FOR 70% ALUMINUM-30% DECALIN SLURRY 37-E

Stable combustion was obtained over an equivalence ratio from 0.7 to 2.1.

III.A.1.6.2. JP-5

Results for combustion chamber Mach numbers of 0.136 and 0.269 obtained with JP-5 fuel are presented in Fig. III.A.3. From Fig. III.A.3. it appears that the efficiency for JP-5 is more pressure dependent than for JP-4. In general it may be concluded that the combustion efficiency obtained with JP-5 is approximately 89% for Mach numbers of 0.136 and 85% for Mach numbers of 0.269 (neglecting the data obtained at a combustor pressure of 100-104 psia). Those data appear to be in error.

Stable combustion was obtained over a range of equivalence ratios from 0.85 to approximately 2 which is not as broad as that obtained with JP-4 fuel.

III.A.1.6.3 Decalin

The combustion efficiencies obtained with decalin as presented in Fig. III.A.4. show more scatter than those for either JP-4 or JP-5. The efficiencies obtained at the low Mach number appear to be more pressure sensitive than those for either JP-4 or JP-5. On the other hand, high efficiencies 95% were obtained at both 0.13 and 0.26 Mach numbers.

In any case it may be concluded that the combustion efficiencies obtained with decalin on the average are higher than those obtained with JP-4 and JP-5 fuels.

Stable combustion was obtained over a range of equivalence ratios from 0.9 to 2.0.

III.A.1.6.4. 70% Tetralin, 30% Decalin

The combustion efficiencies for the 70% tetralin, 30% decalin fuel mixture are presented in Fig. III.A.5. Those data indicate that the combustion efficiency obtained with the blend is more sensitive to combustion chamber Mach number than was observed with either the JP-4 and JP-5 fuels or pure decalin. The data obtained at a combustion pressure of 166 psia may be in error since they are lower than the values obtained at lower combustion pressures, and with all other fuels the higher pressures produced the higher efficiencies.

Stable combustion was obtained over a range of equivalence ratios from 0.9 to 1.65, a more limited range than for the other fuels.

III.A.1.6.5. 70% Aluminum, 30% Decalin

Only preliminary data are presented for the aluminum-decalin slurry fuel in Fig. III.A.6. Time did not permit more extensive evaluation of the slurry fuel. From the data presented for a combustor Mach number of 0.25 it can be seen that combustion efficiency decreases markedly as the equivalence ratio is increased above 1. The combustion efficiency of approximately 88% was obtained for equivalence ratios from 0.7 to 1.0. The combustion efficiency does not appear to be independent of combustion pressure. Additional experiments should be conducted to verify this conclusion.

Only one fuel injection orifice configuration was employed. Additional experiments should be conducted to determine an optimum slurry fuel injection system.

III.A.1.7. Conclusions Based Upon Experimental Results

The following conclusions are presented.

III.A.1.7.1. The 90° air inlet angle sudden dump combustor gives combustion efficiencies of 80 to 95% when using a wide variety of fuels.

III.A.1.7.2. The combustion efficiencies obtained with decalin are on the average higher than those obtained with JP-4 or JP-5 fuels.

III.A.1.7.3. The combustion efficiencies obtained with a 70% tetralin-30% decalin blend fuel are lower than those obtained with pure decalin.

III.A.1.7.4. Based upon preliminary results only the combustion efficiencies obtained with the aluminum-decalin slurry was lower than those obtained with the hydrocarbon fuels. This may be a function of the slurry fuel injection system.

III.A.1.8. Recommendations for Additional Experiments

It is recommended that additional experiments be conducted to evaluate the influence upon combustion efficiency of the following parameters:

Employing the 90° air inlet angle combustor:

III.A.1.8.1. Determine the effect of air inlet temperature over the range from 1000 R to 1500 R at combustion pressures from 40 psia to 120 psia.

III.A.1.8.2. Determine the effect of combustor length upon combustion efficiency and thereby establish the minimum combustor length for each fuel.

III.A.1.8.3. Determine the effect of combustor Mach number upon combustion efficiency over a range of Mach numbers from 0.13 to 0.50 for each fuel.

III.A.1.8.4. Determine the effect of the volume between the combustor dome and the air inlet upon combustion efficiency and combustion stability.

Employing the 45° air inlet angle combustor:

III.A.1.8.5. Repeat items A.1.8.1. through A.1.8.4. Data from all experiments will be employed in the development of the analytical model for the sudden dump ramjet combustor.

III.A.1.8.6. Develop a slurry fuel injection system to provide improved dispersion of the slurry fuel.